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The Current Convective Instability and its Application to Diffuse Auroral Scintillation Causing Irregularities

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A stable $\underline{E} \times \underline{B}$ gradient drift geometry can become destabilized by a current along the magnetic field. This type of instability is generically called the current convective instability. This instability may be responsible for the diffuse auroral scintillation causing F region irregularities observed by the DNA Wideband satellite. In these phenomena the northward TEC gradient dominated the altitude electron density gradient. We have investigated a simple plasma fluid model and found that instability results for $-\underline{k} \cdot \underline{V}_d > \underline{k} \cdot (c\underline{E}_o/B_o)(\nu_i/\Omega_i)$ where $\underline{V}_d$ is the relative drift

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20. ABSTRACT (Continued)

(precipitation current) between ions and electrons along $\underline{B}_o$, $\underline{E}_o$ is the westward ambient electric field ($\perp B_o$) and ν_i and Ω_i are the F region ion-neutral collision frequency and ion gyrofrequency.

CONTENTS

THE CURRENT CONVECTIVE INSTABILITY AND ITS APPLICATION TO DIFFUSE AURORAL SCINTILLATION CAUSING IRREGULARITIES

INTRODUCTION

Recently data from the DNA Wideband satellite have exhibited high latitude (auroral and subauroral) scintillation enhancements which appear to be associated with north-south gradients in total electron content [TEC; see *Fremouw et al.*, 1977; *Rino et al.*, 1978]. *Rino et al.*, [1978] have shown that a regularly occurring scintillation enhancement can be identified in the nighttime auroral zone data, in the region of diffuse auroral particle precipitation. It is also shown that this enhancement is due to sheet like F region ionospheric irregularities. These irregularities occur near where the TEC gradient points northward, i.e., increasing TEC as one goes northward. In addition, it appears that a d.c. electric field points either westward or northwest and that there is a very shallow plasma density gradient in altitude, i.e., the northward TEC gradient dominates (C. Rino, private communication, 1978). The diffuse auroral precipitation deposits low energy particles into the F region without any E region current systems being set up.

At first glance, with the dominant TEC gradient pointing northward, the ambient magnetic field, $\underline{B}_o$, pointing down and the d.c. electric field horizontal, this would appear to be a prime geometry for the usual F region $\underline{E} \times \underline{B}$ gradient drift instability. However, with the d.c. electric field pointing westward or northwest, the configuration is stable (see Fig. 1; the electric field would have to point eastward for instability). The saving feature, however, is the diffuse auroral precipitation (current) which acts to destabilize the above geometrical configuration (see Fig. 1). The conditions of having a current along $\underline{B}_o$, a density gradient, ∇n_o, perpendicular to $\underline{B}_o$, and an electric field perpendicular to $\underline{B}_o$ and possibly ∇n_o can result in instability and these types of instabilities are generically called current convective instabilities [*Kadomtsev*, 1965].

This type of instability has been applied to the positive column of laboratory gas discharges [*Lehnert*, 1958; *Hoh and Lehnert*, 1960; *Kadomtsev and Nedospasov*, 1960; *Kadomtsev*, 1965], but to our knowledge has not been applied to the conditions in the F region ionosphere. A simple physical picture of the instability is as follows (see Fig. 1). First let us discuss the usual F region $\underline{E} \times \underline{B}$ gradient drift instability picture. In the upper part of Figure 1 the horizontal line represents an unperturbed contour of constant electron density, the background zero order electron density gradient points upward (northward), there is a horizontal d.c. electric field (eastward), and the ambient magnetic field, $\underline{B}_o$, is into the picture. Now let the density be perturbed by a small amplitude horizontal sinusoidal variation ($\underline{k}$ parallel to $\underline{E}_o$). The ions Pedersen drift to the right relative to electrons whose Pedersen drift is for all purposes negligible in the F region (the dashed sinusoid represents the electrons, the solid the ions). This gives rise to space charges (+ and −) which in turn cause small scale electric fields $\underline{E}'$,

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directed alternately to the left and right. In this geometry (eastward $\underline{E}_0$), the corresponding $\underline{E}' \times \underline{B}_0$ drifts will then carry the enhanced regions downward (southward) and the depleted regions upward (northward) so that they both will appear to grow in amplitude against the background density (convective instability). If $\underline{E}_0$ were to point westward, as in the diffuse auroral case, the perturbations would disappear, i.e., the situation would become stable (also if ∇n_0 were reversed in Fig. 1 stability would result).

Now let us discuss the $\underline{E} \times \underline{B}$ geometry with a magnetic field aligned current as illustrated in the lower part of Figure 1. There is an ambient electric field, $\underline{E}_{0\perp}$, perpendicular to $\underline{B}_0$ (pointing down) and pointing to the left (westward), the density gradient, ∇n_0, is into the picture (northward), the current, $\underline{j}_{0\parallel}$, is anti-parallel to $\underline{B}_0$, the horizontal line across the perturbation (where $\underline{k}$ is in the $\underline{E}_{0\perp} - \underline{B}_0$ plane and perpendicular to ∇n_0) represents the unperturbed constant electron density contour. In this picture without $\underline{j}_{0\parallel}$ the system would be stable to the $\underline{E} \times \underline{B}$ instability (see previous paragraph). The projection on $\underline{k}$ of the ion Pedersen drift caused by $\underline{E}_{0\perp}$ results in a drift of the ions along $\underline{k}$ such that it would result in stability. However, the direction of $\underline{j}_{0\parallel}$ implies that the relative drift between ions and electrons (in the frame where the electrons are at rest) is anti-parallel to $\underline{B}_0$. This motion projected on $\underline{k}$ results in establishing space charges which give rise to small scale electric fields $\underline{E}''$ as shown in Fig. 1 (note that the Pedersen motion due to $\underline{E}_{0\perp}$ results in small scale electric fields opposed to $\underline{E}''$). If the particle motion projected on $\underline{k}$ is dominated by the $\underline{j}_{0\parallel}$ rather than $\underline{E}_{0\perp}$ then the space charges give rise to total small scale electric fields, $\underline{E}'$, as depicted in the figure. The corresponding $\underline{E}' \times \underline{B}_0$ drifts will then carry enhanced regions out (southward) of the figure and depleted regions into (northward) the figure so that they both will appear to grow in amplitude against the background density. From this picture the instability criterion is $|\underline{k} \cdot \underline{V}_d| > |\underline{k} \cdot (c\underline{E}_{0\perp}/B_0)(\nu_i/\Omega_i)|$, where $\underline{j}_{0\parallel} = n_0 e \underline{V}_d$ and ν_i and Ω_i are the ion-neutral collision frequency and ion gyrofrequency, respectively. This will be mathematically derived in the next section. The lower figure can be made similar to the upper figure by noting that $\underline{j}_{0\parallel} = n_0 e \underline{V}_d = \sigma_\parallel \underline{E}_{0\parallel}$ and then setting $\underline{E}_0 = \underline{E}_{0\perp} + \underline{E}_{0\parallel}$. We note that in the above picture making $\underline{j}_{0\parallel}$ in the direction of $\underline{B}_0$ or rotating $\underline{k}$ by 90° about $\underline{E}_{0\perp}$ or $\underline{B}_0$ results in stability. We also note that the above picture for instability is valid even for $\underline{E}_{0\perp} = 0$. If $\underline{E}_{0\perp}$ were reversed in direction the parallel current would enhance an already unstable situation.

This instability also has $k_\parallel << k_\perp$ (see next section) and so the irregularities generated will be field aligned. This current convective instability can directly result in long wavelength scintillation causing F region ionospheric irregularities in the diffuse auroral region. In the next section we present the theory and the last section contains the summary.

THEORY

In this section we present a theoretical model for a long wavelength fluid type plasma instability which may account for the scintillation causing diffuse auroral F region ionospheric irregularities. For our model we take the electron density gradient to be pointing northward (y), the ambient electric field $\underline{E}_0$ is in the westward direction (x) and the magnetic field points downward (z). In our simple model we have equated the TEC gradient with a gradient in density. We assume that the horizontal (northward) electron density gradient is much sharper than the altitude density gradient, which we neglect. Our basic equations are

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \underline{V}_\alpha) = 0 \tag{1}$$

$$\underline{V}_i = \frac{c}{B_o} \underline{E} \times \hat{z} - \frac{c}{B_o} \frac{\nu_i}{\Omega_i} \underline{E}_\perp + \frac{c}{B_o} \frac{\Omega_i}{\nu_i} \underline{E}_\parallel + \underline{V}_{io\parallel} \tag{2a}$$

$$\underline{V}_e = \frac{c}{B_o} \underline{E} \times \hat{z} - \frac{c}{B_o} \frac{\Omega_e}{\nu_e} \underline{E}_\parallel + \underline{V}_{eo\parallel} \tag{2b}$$

$$\nabla \cdot \underline{j} = 0, \; \underline{j} = \Sigma n_\alpha q_\alpha \underline{V}_\alpha \tag{3}$$

where the subscript α is the species label (e is electron, i is ion), n is density, $\underline{V}$ is velocity, ν is collision frequency, q is charge, E is electric field, B_o is the ambient magnetic field, $\hat{z} = \underline{B}_o/|B_o|$, $\Omega_\alpha = |q_\alpha|B_o/m_\alpha c$, $\underline{j}$ is the current and $\underline{V}_{\alpha o}$ represents the diffuse auroral particle precipitation velocity along $\underline{B}_o$ ($_\parallel$ and $_\perp$ denote parallel and perpendicular to $\underline{B}_o$) which results in a zero order current. In the momentum transfer eqn. (2), we have neglected inertial and temperature effects, and included electron collisions to first order for completeness. Equation (2) is valid for F region ionosphere altitudes ($\nu_\alpha/\Omega_\alpha << 1$). In (2a) ν_i is taken to mean ion-neutral collisions, whereas in (2b) ν_e is really electron-ion collisions. We have neglected the electron Pedersen drift compared with the ion Pedersen drift.

We assume quasi-neutrality so that $n_e \approx n_i \approx n$ and our final equations are the electron continutiy equation, electron and ion momentum equations, and $\nabla \cdot \tilde{\underline{j}} = 0$. The equations are then linearized such that $n = n_o(y) + \tilde{n}$, $\underline{E} = E_o \hat{x} - \nabla\tilde{\phi}$, $\underline{V}_\alpha = \underline{V}_{\alpha o} + \tilde{\underline{V}}_\alpha$ with the perturbed quantities $\tilde{n}$, $\tilde{\underline{V}} \propto \exp i\,[k_x x + k_\parallel z - \omega t]$, where $\omega \equiv \omega_r + i\gamma$. We then obtain

$$\underline{V}_{io} = \underline{V}_{io\parallel} + \frac{c}{B_o} \frac{\nu_i}{\Omega_i} E_o \hat{x} - \frac{c}{B_o} E_o \hat{y} \tag{4a}$$

$$\underline{V}_{eo} = \underline{V}_{eo\parallel} - \frac{c}{B_o} E_o \hat{y} \tag{4b}$$

$$\tilde{\underline{V}}_i = - \frac{e}{m_i \nu_i} ik_\parallel \tilde{\phi} \hat{z} - \frac{c}{B_o} \frac{\nu_i}{\Omega_i} ik_x \tilde{\phi} \hat{x} + \frac{c}{B_o} ik_x \tilde{\phi} \hat{y} \tag{5a}$$

$$\tilde{\underline{V}}_e = \frac{e}{m_e \nu_e} ik_\parallel \tilde{\phi} \hat{z} + \frac{c}{B_o} ik_x \tilde{\phi} \hat{y} \tag{5b}$$

Substituting (4) and (5) into the linearized versions of (1) and (3) results in the following determinant set of equations.

$$i(\omega - k_\parallel V_{eo\parallel})\, \tilde{n} - \left(\frac{c}{B_o} ik_x \frac{\partial n_o}{\partial y} - \frac{e}{m_e \nu_e} k_\parallel^2 n_o\right) \tilde{\phi} = 0 \tag{6}$$

$$i\left[\frac{c}{B_o} k_x E_o \frac{\nu_i}{\Omega_i} + V_d k_\parallel\right] \tilde{n} + n_o \left[k_\parallel^2 \left(\frac{e}{m_i \nu_i} + \frac{e}{m_e \nu_e}\right) + \frac{c}{B_o} k_x^2 \frac{\nu_i}{\Omega_i}\right] \tilde{\phi} = 0 \tag{7}$$

where $V_d \equiv V_{io\parallel} - V_{eo\parallel}$ and (6) and (7) are from linearizing the electron continuity equation and $\nabla \cdot \underline{j} = 0$ equation, respectively.

From (6) and (7) one obtains

$$\omega' = \frac{-i\,\dfrac{1}{n_o}\dfrac{\partial n_o}{\partial y}\left[\dfrac{c}{B_o}E_o\dfrac{\nu_i}{\Omega_i}+V_d\dfrac{k_\parallel}{k_x}\right]+\dfrac{k_\parallel^2\,\Omega_e}{k_x\,\nu_e}\left[\dfrac{c\,\nu_i}{B_o\,\Omega_i}E_o+\dfrac{k_\parallel}{k_x}V_d\right]}{\left(\dfrac{\Omega_i}{\nu_i}+\dfrac{\Omega_e}{\nu_e}\right)\dfrac{k_\parallel^2}{k_x^2}+\dfrac{\nu_i}{\Omega_i}} \tag{8}$$

where $\omega' \equiv \omega - k_\parallel V_{eo\parallel}$. From $\omega \equiv \omega_r + i\gamma$ we then obtain

$$\gamma = \frac{-\dfrac{1}{n_o}\dfrac{\partial n_o}{\partial y}\left[\dfrac{c}{B}E_o\dfrac{\nu_i}{\Omega_i}+V_d\dfrac{k_\parallel}{k_x}\right]}{\left(\dfrac{\Omega_i}{\nu_i}+\dfrac{\Omega_e}{\nu_e}\right)\dfrac{k_\parallel^2}{k_x^2}+\dfrac{\nu_i}{\Omega_i}} \tag{9}$$

which for the lower F region ($\nu_i/\Omega_i >> \nu_e/\Omega_e$) becomes

$$\gamma \approx \frac{-\dfrac{1}{n_o}\dfrac{\partial n_o}{\partial y}\left[\dfrac{c}{B_o}E_o\dfrac{\nu_i\nu_e}{\Omega_i\Omega_e}+V_d\dfrac{k_\parallel}{k_x}\dfrac{\nu_e}{\Omega_e}\right]}{\left(\dfrac{k_\parallel}{k_x}\right)^2+\dfrac{\nu_i\nu_e}{\Omega_i\Omega_e}} \tag{10}$$

We see that in (9) or (10) γ is independent of $|k|$ and only depends on the angle that $\underline{k}$ makes with $\underline{B}_o$. In the denominator of (9), the first term (in brackets) multiplying $(k_\parallel/k_x)^2$ comes from the parallel motion of the ions and electrons; whereas, the remainder of the denominator comes from the ion Pedersen motion. It should be noted that the instability is essentially unaffected by the current direction. Thus, downward currents work just as well as upward currents. In (9) if we set $k_\parallel = 0$ we obtain $\gamma = -(n_o^{-1}\partial n_o/\partial y)\ (cE_o/B_o)$ which is the usual result for the $\underline{E} \times \underline{B}$ gradient drift instability. For our geometry this shows γ is negative which implies stability. For instability in (9) $\gamma > 0$ which implies

$$\frac{c}{B_o}E_o\frac{\nu_i}{\Omega_i}+V_d\frac{k_\parallel}{k_x} < 0 \tag{11}$$

This says that for instability, with the westward $\underline{E}_o$, we must have $V_d\,k_\parallel/k_x < 0$ and $|V_d\,k_\parallel| > (k_x cE_o/B_o)\ (\nu_i/\Omega_i)$, which is exactly the condition set forth on the basis of our physical picture presented in the first section.

For very large parallel currents (or $\underline{E}_o = 0$) such that $|V_d k_\parallel| >> (k_x cE_o/B_o)\ (\nu_i/\Omega_i)$ we have from (9)

$$\gamma = \frac{-\dfrac{1}{n_o}\dfrac{\partial n_o}{\partial y}V_d\dfrac{k_\parallel}{k_x}}{\left(\dfrac{\Omega_i}{\nu_i}+\dfrac{\Omega_e}{\nu_e}\right)\left(\dfrac{k_\parallel}{k_x}\right)^2+\dfrac{\nu_i}{\Omega_i}} \tag{12}$$

We can maximize this growth with respect to $\Theta \equiv k_\parallel/k_x$. The growth rate maximizes for $\Theta \equiv \pm\,\{\nu_i/\Omega_i[(\Omega_i/\nu_i) + (\Omega_e/\nu_e)]^{-1}\}^{1/2}$. From (9) the growth rate maximizes, in general, for

$$\Theta = -(cE_o/B_oV_d)(\nu_i/\Omega_i) \pm \{(cE_o/B_oV_d)^2(\nu_i/\Omega_i)^2 + (\nu_i/\Omega_i)[(\Omega_i/\nu_i) + (\Omega_e/\nu_e)]^{-1}\}^{1/2}$$

For altitudes $\sim$ 350-400km corresponding to the observation altitudes [*Rino et al.*, 1978] $\nu_i/\Omega_i \sim 10^{-4}$, $\nu_e/\Omega_e \sim 10^{-4}$ and this makes $k_{\parallel}/k_x \approx 0.7 \times 10^{-4}$. Consequently for maximum growth the growing perturbations will be nearly perpendicular to the magnetic field. From (12) we obtain for maximum growth

$$\gamma_{max} \approx -\frac{1}{2n_o}\frac{\partial n_o}{\partial y} V_d \left(1 + \frac{\Omega_e \nu_i}{\nu_e \Omega_i}\right)^{-1/2} \tag{13}$$

Equation (13) yields, with $V_d \sim$ -500 m/sec (at a density $n_o \sim 10^5$ cm^{-3} this yield $j_{o\parallel} \sim 8\ \mu$ amps/m^2 which is in line with experimental measurements, R. Vondrak, private communication, 1978) $L \equiv n_o(\partial n_o/\partial y)^{-1} \sim$ 50 km (C. Rino, private communication, 1979) and the above collision frequencies, $\gamma_{max} \approx 3.5 \times 10^{-3}$ sec^{-1}. For a westward electric field $\sim$ 10 mV/m (C. Rino, private communication, 1979) the growth rate is diminished somewhat. For this case from (9) we obtain that the maximum growth rate is $\gamma_{max} \approx 2.7 \times 10^{-3}$ sec^{-1}, which occurs for $k_{\parallel}/k_x \approx 9.4 \times 10^{-5}$. Including pressure effects in the problem introduces diffusive damping in (9). A typical cross-field diffusion coefficient, $D_\perp$, is $\sim$ 0.2 m^2/sec and a parallel diffusion coefficient, $D_\parallel$, is $\sim 10^8$ m^2/sec. In the present study, these effects become important for perpendicular wavelengths, $\lambda_\perp$, $\lesssim$ 100 m and parallel wavelengths, $\lambda_\parallel$, $\lesssim$ 1000 km. However, typical scintillation causing perpendicular wavelengths are $\sim$ 1 km and since $k_\parallel/k_\perp \sim 10^{-4}$ we are considering highly field aligned irregularities. Larger parallel currents, due to precipitation, will of course produce larger growth rates. However, too large a current, $V_d \gtrsim$ 1 km/sec, would excite the collisional electrostatic ion cyclotron instability [*Chaturvedi*, 1976]. It may be noted that the linear theory of the current convective instability proposed here favors a wavevector perpendicular to the TEC gradient (as well as $\underline{B}_o$).

SUMMARY

We have investigated a simple plasma fluid model to account for the diffuse auroral scintillation causing F region ionospheric irregularities observed by the DNA Wideband satellite [*Rino et al.*, 1978]. By taking account of the diffuse auroral particle precipitation (current) the stable $\underline{E} \times \underline{B}$ diffuse auroral geometry (corresponding to the observations) becomes destabilized by this parallel current. For a westward ambient d.c. electric field, $\underline{E}_o$, and a northward dominant electron density gradient, the relative drift velocity between ions and electrons parallel to $\underline{B}_o$, $\underline{V}_d$, must satisfy the condition $-\underline{k} \cdot \underline{V}_d > \underline{k} \cdot (c\underline{E}_o/B_o)(\nu_i/\Omega_i)$ for instability. The maximum growth rate for the instability is $\gamma \approx n_o^{-1}(\partial n_o/\partial y)V_d[1 + (\Omega_e\nu_i/\Omega_i\nu_e]^{-1/2}/2$. The instability is mainly field aligned ($k_\parallel << k_\perp$). The instability is fluid-like in nature and so can directly account for the long wavelength diffuse auroral scintillation causing F region irregularities.

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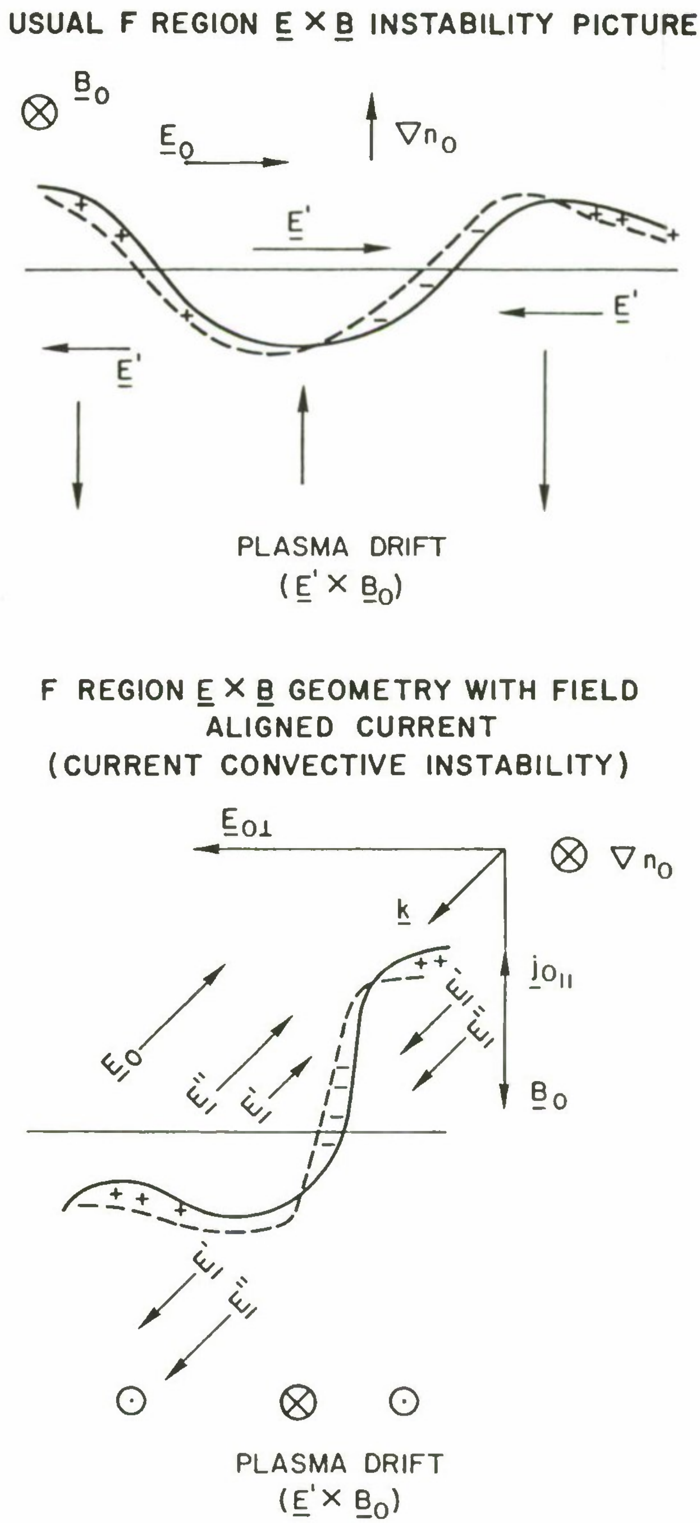

Fig. 1. Simplified physical picture of $\underline{E}\times\underline{B}$ gradient drift instability and current convective instability.

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